Progress in the development of a cold background, flight motion simulator mounted, infrared scene projector for use in the AMRDEC Hardware-in-the-Loop facilities

Thomas M. Cantey[a], D. Brett Beasley[a], Matt Bender[a], Tim Messer[a],
Daniel A. Saylor[a] and Jim Buford[b]
[a]Optical Sciences Corporation, 6767 Old Madison Pike Ste.195, Huntsville, Alabama 35808
[b]U.S. Army Research, Development, and Engineering Command, Aviation & Missile RDEC, Redstone Arsenal, Alabama

ABSTRACT

This paper will present the progress on AMRDEC's development of a cold background, flight motion simulator (FMS) mountable, emitter array based projector for use in hardware-in-the-loop systems simulation. The goal for this development is the ability to simulate realistic low temperature backgrounds for windowed/domed seekers operating in tactical and exo-atmospheric simulations. The projector has been developed to operate at -10 degrees Celsius in order to reduce the apparent background temperature presented to the sensor under test. The projector system includes a low temperature operated Honeywell BRITE II emitter array, refractive optical system with zoom optics, integrated steerable point source and high-frequency jitter mirror contained within an FMS-mountable environmental chamber. This system provides a full-FOV cold background, two-dimensional dynamic IR scene projection, a high dynamic range independently steerable point source and combined optical path high frequency jitter control. The projector is designed to be compatible with operation on a 5 axis electric motor driven Carco flight motion simulator.

Keywords: infrared, scene projection, simulation, hardware-in-the-loop, apparent temperature,

1.0 INTRODUCTION

1.1 AMRDEC HWIL facilities

The Aviation and Missile Research, Engineering, and Development Center (AMRDEC) under the command of the U.S. Army Research, Development and Engineering Command (RDECOM) at Redstone Arsenal, Huntsville, Alabama, has an extensive history of applying many types of modeling and simulation (M&S) to weapon system development and has been a particularly strong advocate of hardware-in-the-loop (HWIL) simulation and test for many years. The AMRDEC was previously under the command of the U.S. Army Aviation and Missile Command (AMCOM). The AMRDEC has been providing a full range of simulation support to Army Program Executive Officers (PEOs), Project Managers (PMs), other Armed Services agencies, and certain U.S. allies over the past 40 years. In addition, AMRDEC has M&S support relationships with the U.S. Army Space and Missile Defense Command (SMDC), and the Redstone Technical Test Center (RTTC).

Within the AMRDEC, the Advanced Simulation Center's (ASC) role is to provide a dedicated, government-owned, high fidelity, verified and validated simulation and test tool to assist the project office and prime contractor during missile system development, test, production, and fielding by providing value-added HWIL capabilities. The ASC consists of fourteen (14) HWIL facilities and focuses on the engineering-level simulations that pertain to the missile elements. The ASC is divided into three main areas: Imaging Infrared System Simulation (I^2RSS), Radio Frequency System Simulation (RFSS), and Multi-Spectral System Simulation (MSSS). The I^2RSS supports imaging and non-imaging infrared missile programs in both the near, mid and long wave infrared wavebands as well the visible waveband. The RFSS supports the X, K, Ka, and W band radio frequency missile. The MSSS supports the common

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2005**	2. REPORT TYPE	3. DATES COVERED **00-00-2005 to 00-00-2005**
4. TITLE AND SUBTITLE **Progress in the development of a cold background, flight motion simulator mounted, infrared scene projector for use in the AMRDEC Hardware-in-the-Loop facilities**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Optical Sciences Corporation,PO Box 8291,Huntsville,AL,35808**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES **The original document contains color images.**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**11**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

aperture and/or simultaneous imaging infrared, visible, semi-active laser (SAL) and/or millimeter wave (Ka and W band) missile programs.

1.2 Cool background requirements in HWIL testing

AMRDEC's ASC currently tests many types of seeker missile systems, including imaging infrared systems. The ASC employs the use of state-of-the-art infrared scene projectors to support dynamic infrared scene simulations in testing of these missile systems. Typical infrared scene projector (IRSP) configurations present a dynamic range for any given thermal scene of 15 ºC to 500 ºC. Many infrared scenes however call for apparent temperatures that fall below the minimum apparent temperature achievable by these typical IRSP test configurations. Examples include winter or artic scenes for tactical missile systems, and space background for theatre missile systems. Non-windowed (exo-atmospheric) theatre based seekers require cryogenic backgrounds and are beyond the scope of this effort. However, windowed theatre seekers and tactical seekers have apparent minimum background temperature requirements within 10s of degrees of room temperature. Moderate reduction of the apparent background temperature can add significantly to the range of operational scenarios supported by the projector system. Previous approaches to attaining these moderate reductions in background have largely focused on 'table top' systems confined to large, fixed spaces. The most realistic simulations, however, are provided when coupling the UUT and the IRSP within a five-axis flight motion simulator (FMS). The challenges of integrating a cooled state-of-the-art infrared scene projector system within the limited constraints of the FMS are addressed within this paper.

2.0 GOALS AND IRSP MISSION

The overall goal of this development effort was the design, manufacture and testing of an FMS-mountable IRSP capable of achieving MWIR apparent temperature background levels in the range of 260-270 Kelvin, a reduction of 20-30 Kelvin from typically table-top, room-temperature IRSP systems. Secondary goals included the integration of auxiliary capabilities within the IRSP such as continuous zoom, an independent high temperature point source, and high frequency LOS motion.

The IRSP is to be mounted on the forth axis of an all-electric 5-axis flight motion simulator (FMS). The design of the FMS constricted the projector to a tight volume and weight budget. The volume restrictions required all aspects of the projector system to conform to a 32.5" x 17" x 19.5" box cantilevered off the forth axis.

The UUT LOS intercepts the IRSP volume near the center of the side facing the UUT, thereby further complicating the optical design. Due to the physical size of the source package and optical train, the optical path would have to be folded into a circuitous path within the enclosed volume. The advanced auxiliary features required the mechanical and optical consideration of dual object planes for a point source and dynamic emitter array, the zoom optics, a high-frequency jitter mirror, and a low-frequency steering mirror.

The weight constraint of the IRSP was not as rigid as the volume constraints. Unlike the repercussions of exceeding the volume constraints, excess weight of the IRSP would simply incur a penalty of reduced performance within the outer two axis of the five axis FMS. Based on the desired operating performance level of the FMS, an IRSP goal weight of 75 pounds was selected.

3.0 SYSTEM OVERVIEW

3.1 Overview

The FMS IRSP is a MWIR scene simulator compatible with FMS mounting and provides a broad range of capability. The FMS IRSP consists of the following subsystems: mechanical framework, enclosure/shroud, optics, two dimensional emitter array and electronics, high frequency jitter mirror and electronics, point source steering mirror and electronics, point source, thermal monitoring probes and cooling subsystem.

3.2 2004 Status

The status of the FMS-mountable IRSP system was previously presented at the 2004 SPIE Defense & Security Symposium[1]. In April 2004, several major goals had been attained in the development of the FMS IRSP. First, the pathfinder projector, referred to as the 'YUGO' projector, had been designed, assembled and tested. This successfully demonstrated many of the mechanical, electrical, and cooling techniques to be applied in the final FMS IRSP. Testing of the YUGO also established the initial overall system performance, capturing the relationship between the MWIR apparent temperature and the hardware operating temperature. Second, the optical subsystems of the FMS IRSP had been designed, procured and integrated into the mechanical structure of the FMS IRSP. Small, FMS-compatible electronics for supporting the operation of the emitter array had also been procured. Lastly, an initial interface to a Honeywell emitter array was made and imagery through the system was captured. Figure 1 shows a photograph of the FMS IRSP as it existed in April 2004.

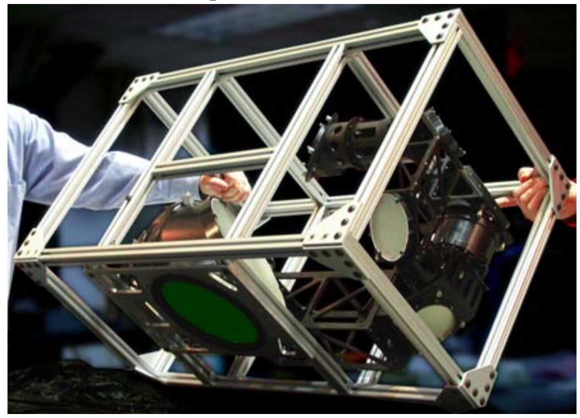

Figure 1: 2004 FMS IRSP

4.0 2005 DEVELOPMENTS

This section discusses the FMS IRSP developments over the previous year. Packaging of the various subsystems, integration of the internal cooling system, and routing of the necessary electrical and cooling lines were primary areas of effort. Testing of the environmental control system was also a major milestone accomplished this year. Test results for the minimum apparent MWIR temperature attained with the FMS IRSP are discussed below along with MWIR imagery collected from the system.

4.1 Cooling and Packaging

As with the pathfinder 'YUGO' projector, the foundational framework structure of the FMS IRSP is composed of modular extruded aluminum components manufactured by 80/20 Incorporated. This material provides a lightweight and robust framework that can be quickly modified and reassembled. All subsystem components of the FMS IRSP are anchored to this framework. Components, such as the optical train, which may be cooled to temperatures significantly below room temperature, are attached using low thermal conductivity materials thereby providing a thermal barrier between the cooled elements and the frame. Where significant mechanical interfaces between the cooled interior elements and the exterior frame were required, a low-conductivity glass-epoxy material (G-10) was used. Figure 2 illustrates the aluminum framework and interface plates composed of the low conductivity G-10 material.

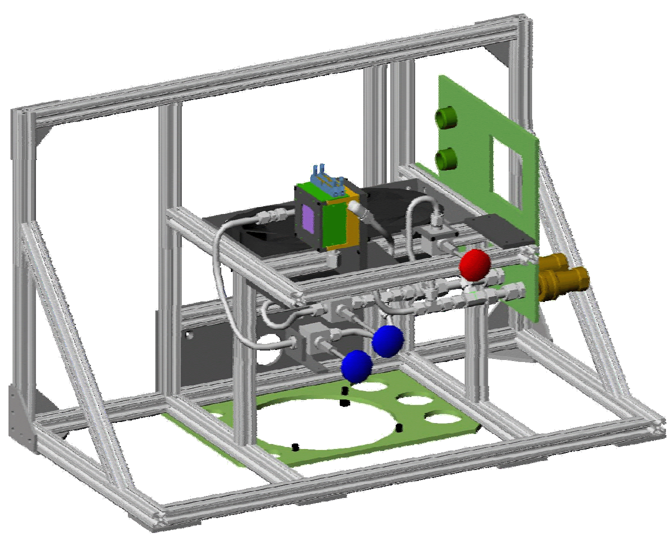

Figure 2: FMS IRSP Cooling Subsystem

Previous work on the pathfinder projector demonstrated the effectiveness of cooling the emitter array and optical hardware. However, the FMS IRSP differs from the pathfinder system in several key aspects with respect to cooling the hardware. The pathfinder projector employed a fixed focus collimator whose optical elements were contained within a single housing comprised of a continuous aluminum tube. This type of optical hardware lent itself easily to a conductive cooling approach consisting of copper tubing wound around the collimator. Conversely, the FMS IRSP optical system consists of three independent optical trains. The optics are housed in unique mechanical mounts which have been 'light-weighted' by removing material not required for mechanical stability. The mechanical design of these optics was not conducive to a conductive cooling scheme. The cooling subsystem for the FMS IRSP was based on a mixture of conductive cooling attained through direct contact with the coolant, and convective cooling attained through the use of a closed cycle chiller, heat-exchanger and forced air.

Figure 2 above also illustrates the cooling subsystem hardware employed within the FMS IRSP. The cooling system consists of an on-board heat-exchanger, fans, and plumbing to the heat-exchanger, array, and point source. An ultra low temperature closed cycle chiller and insulated stainless steel hoses provide coolant to the FMS IRSP. Flow through each leg of the coolant paths (emitter array, heat-exchanger, and point source) can be independently controlled via manual valves. Fans located near the heat-exchanger force air across the cooling fins and circulate the air throughout the enclosed volume. The fans can be independently controlled (on/off) through a solid state relay by the PC to assist in the control of the optics and enclosure temperature. The optical hardware was intentionally designed with as many air pathways as possible to facilitate a quick and uniform cool-down process. Figure 3 is a photograph of the assembled projector. The coolant line valves can be clearly seen (red and blue knobs) along with the plumbing. The heat-exchanger is enclosed in the back portion of the assembly and is not visible in this picture.

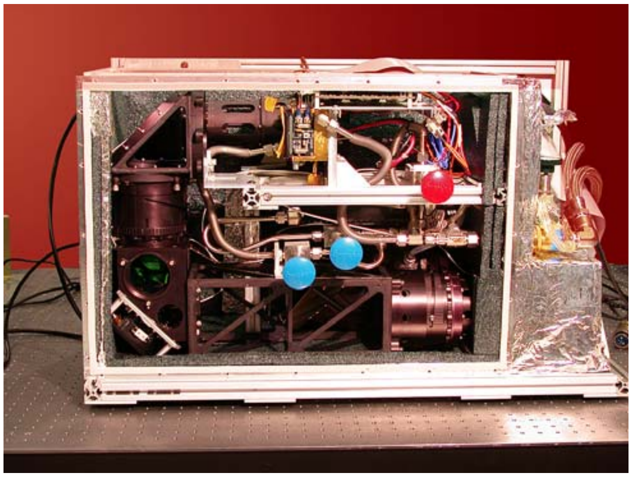

Figure 3: 2005 FMS IRSP

A shroud was constructed to provide the walls for the environmental enclosure in order to isolate the optical components of the projector from the outside world. The environmental enclosure makes up ~80% of the total volume of the FMS IRSP. The shroud consists of an inch or more of closed cell foam insulation covered by a multi-layer aluminized Mylar radiation blanket. The aluminized Mylar shield also acts as an added vapor barrier. Slight over-pressurization and a purge of the enclosure using the dry nitrogen purge gas insures an extremely low dew point temperature for safe operation at low temperatures. Two side panels of the shroud may be easily removed for access to the enclosed hardware.

4.2 Sub-system Integration

Most major subsystem components have been physically integrated into the FMS IRSP. These subsystems include the emitter array analog electronics, jitter mirror, and point source steering mirror.

The emitter array analog electronics are a commercially available off-the-shelf item manufactured by Dynetics Corporation. These analog electronics are smaller than any previously manufactured making them the most compatible with the FMS IRSP. The Dynetics electronics directly connect to the emitter array top paddle board and are mechanically secured through this connection as well as being secured through the electronics housing to the rear of the cooling block bracket. The electronics are actively cooled by small circulation fans located next to the electronics boards on the housing. A bulkhead feed-through panel allows the necessary cables to penetrate the environmental shroud enclosure. The bulkhead panel is composed of a low thermal conductivity G10 glass-epoxy material. A photograph of the FMS IRSP system, including a blow up of the array and supporting electronics is shown in Figure 4.

The jitter mirror subsystem is an integral part of the FMS IRSP optical train and is common to the 2-D emitter array optical path and the point source optical path. This subsystem provides the capability for inserting small amplitude, high-frequency line-of-sight jitter to simulate the vibrational effects imposed on the unit-under-test due to thruster firings. The jitter mirror is shown in Figure 4 integrated into the FMS IRSP package. Closely spaced jitter mirror drive electronics are mounted within the FMS IRSP but outside the environmental shroud. A digital-to-analog VME card, located in a 19” rack not mounted to the FMS, provides the input to these electronics for controlling the jitter mirror.

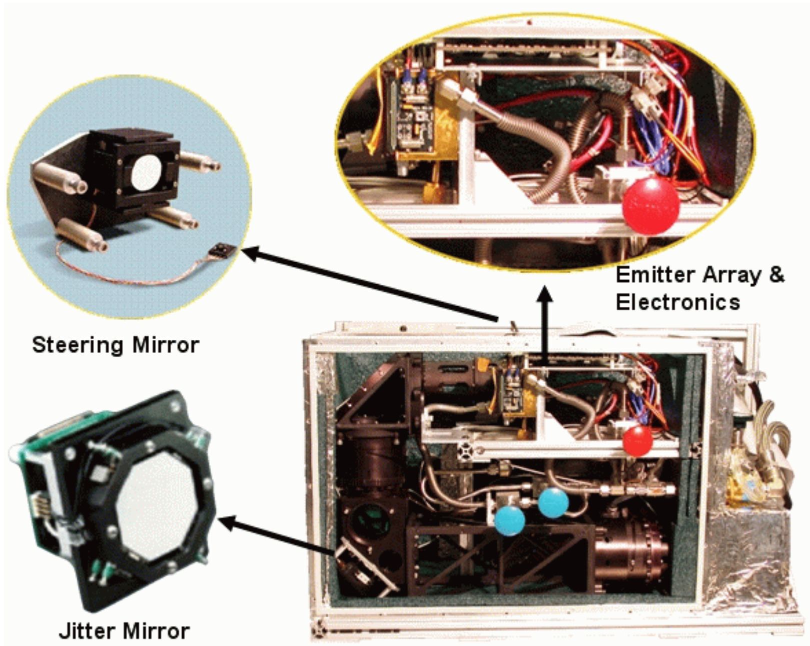

Figure 4: Subsystem Integration

The steering mirror is an open-loop two-axis piezoelectric fast steering mirror which independently controls the apparent angular location of the point source with respect to the 2-D emitter array image. The point source and accompanying steering mirror provide the capability for simulating high temperature counter-measures, debris, and other relatively small hot items within the FOV of the unit-under-test. Drive electronics for the steering mirror, like the jitter mirror, are housed within the FMS IRSP framework but outside the environmental shroud. Figure 4 also shows a picture of the steering mirror which is integrated into the FMS IRSP. A custom VME interface board provides the input to the steering mirror and electronics from a 19” rack located off the FMS.

4.3 System Control

The FMS IRSP is composed of several state-of-the-art subsystems each requiring independent, yet integrated, control. This section describes the COTS and custom systems employed to achieve this control for calibration, characterization, and closed-loop HWIL operation.

The hardware for controlling the FMS IRSP is primarily contained within two chassis: (1) a PCI-based PC chassis and (2) a VME-based 19” rack mounted chassis. Figure 5 below illustrates the variety of interface boards employed in the control of the FMS IRSP subsystems.

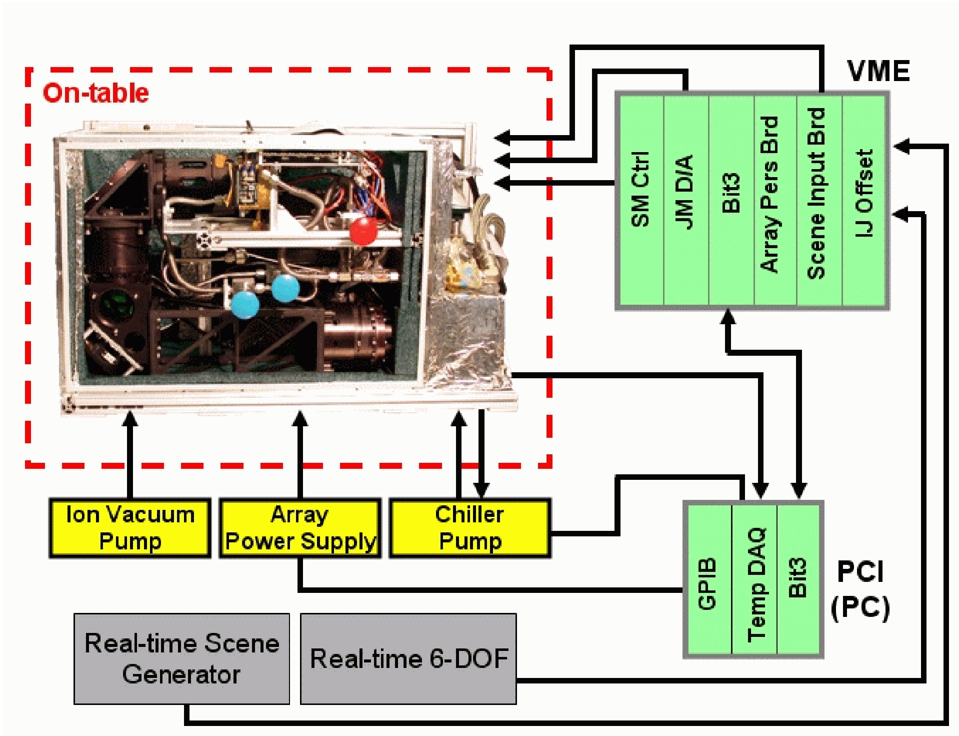

Figure 5: FMS IRSP Control Hardware

The specific hardware device implemented is identified and discussed below for each of the major subsystems.

- Emitter Array: The emitter array, and accompanying analog electronics, is driven through a COTS set of digital electronics manufactured by Dynetics Corporation. These digital electronics consist of a two board 9U VME set and receive the necessary real-time imagery through a DDO2 link to the SGI scene generator computer.
- Jitter Mirror: The jitter mirror drive electronics receive an analog signal from a VMIC VME based D/A card. Command signals are input into the D/A card from the real-time HWIL control system through a VME bus bridge.
- Steering Mirror: The on-board steering mirror drive electronics receive their data from a custom 6U VME board built by AMRDEC. The custom board sends TTL signals to the drive electronics and control the movement of the steering mirror and thus the point source position in the scene.
- Point Source: The semiconductor laser will be driven by a custom on-board analog amplifier card designed and built by AMRDEC. This board provides a 0-2 Amp drive current with a response time of <100nsec. Another custom AMRDEC 6U VME board will drive the amplifier card from a 19" rack. This board will receive amplitude input information from the real-time HWIL control system.
- Resistance Temperature Device (RTD): RTDs are located throughout the FMS IRSP and are monitored by a National Instruments PCI data acquisition (DAQ) card housed within the PC chassis.
- Other:
    - Array Power Supply: The array power supply, located off the FMS, is controlled via a COTS GPIB card located in the PCI bus of the control PC chassis. Monitoring of the current supplied to the emitter array is performed by the system software to prevent over current and protect the emitter array.
    - Heat-exchanger Fans: The heat-exchanger fans are operated by a solid state relay which is digitally controlled through the PCI DAQ card. Closed-loop control of the fans provides a stable optical system temperature independent of the emitter array temperature.

- o Ion Pump: The ion-pump is driven by an off-table power supply controller. No integration into either control bus has been made for monitoring this sub-system.

4.4 Testing

Preliminary cool-down testing of the FMS IRSP has been performed. Figure 6 below shows a screen capture of a LabVIEW application for controlling, monitoring and recording temperatures over time at eight different locations on the FMS IRSP. Two additional data points are also plotted: the chiller set point and the chiller bath temperature. The chiller temperature, denoted by the lowest two lines, was cycled through four different set points ranging from near room temperature (15 ºC) to –15 ºC. The eight locations monitored within the FMS IRSP fall into three groups on the plot: (1) the lowest group contains the input line, output line, and emitter array cooling block; (2) the middle group consists of four locations on the optical subsystem; and (3) the final temperature probe, shown as the uppermost line, represents the temperature of the outer window frame. The input, output, and array temperatures consistently rest at ~5 degrees above the chiller temperature. The optical assembly stabilizes approximately 3 degrees above the input line temperature. Lastly, the output window frame, conductively attached to the optical assembly through the mounting, remains several degrees above the temperature of the optics. At -15 ºC, the lowest chiller set point temperature during this test, the output window frame temperature reached the laboratory dew-point temperature at 0 ºC and resulted in condensation and frost appearing on the window and window frame. An external fan was used at this point to move room temperature air across the window and slightly warm the window and window frame. This warming is clearly evident in the plot (see group #3 in Figure 6) and a refinement of the process will be implemented to insure the window remains as low as possible while still above the dew-point.

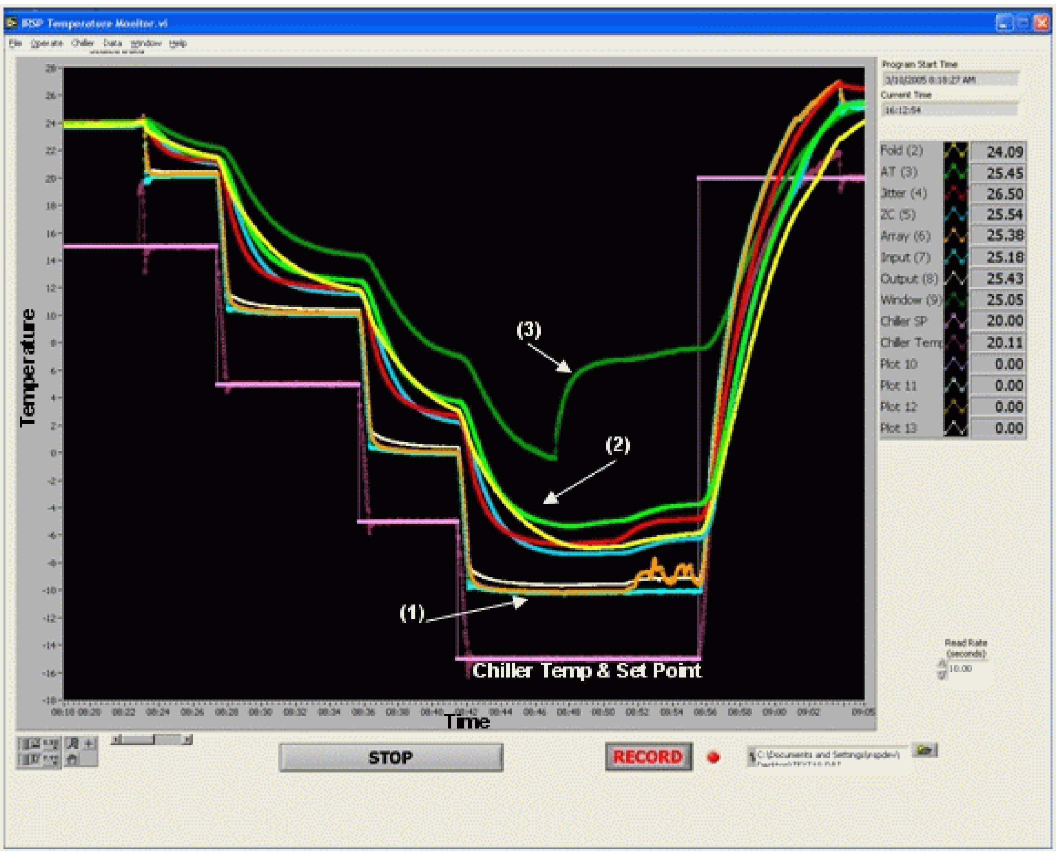

Figure 6: Cool-down Testing

One additional item to note in the cool-down plot is the behavior of the emitter array cooling block temperature during emitter array operation. Upon reaching stabilization at the lowest temperature, the emitter array was operated using extended full-FOV imagery at low-moderate current levels. The array temperature is shown in the second group from the bottom and can be recognized by the dynamic high frequency oscillations near the end of the testing. This represents the periods where imagery was driven on the array. Operating the array at low to moderate drive current over the full FOV clearly creates measurable changes in the temperature of the array cooling block. This may indicate the need for some applications to use active temperature control of the cooling block in order to maintain a high degree of calibration.

The previous data illustrates the behavior of the hardware during cool-down. Of utmost importance, with respect to cooling the hardware, is the final system level performance. This is captured in the minimum apparent MWIR background temperature attained at a given cooling level. The apparent MWIR temperature was directly determined using a MWIR InSb camera and a blackbody for reference. In the first step of the process, the response of the MWIR camera to known blackbody temperature values was logged. The 'curve fit' to this camera response was then extrapolated below the reference blackbody dew-point to cover the apparent temperature range expected. The camera then viewed the FMS IRSP and the corresponding count value was compared to the blackbody data. These results are shown in Figure 7 below, where the measured counts while viewing the FMS IRSP (~1100 counts) are marked by the star. At a chiller temperature of –20 ºC, attaining an emitter array cooling block temperature of –14.5 ºC and an optical system temperature of –10 ºC, an MWIR apparent temperature of –10 ºC was measured.

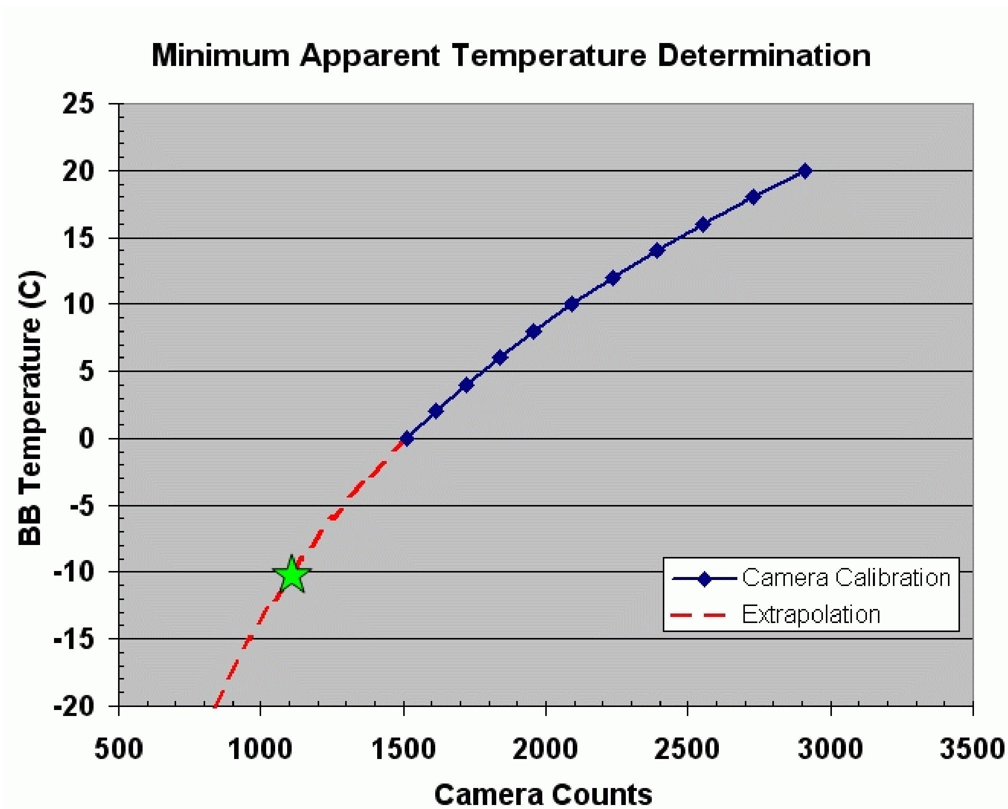

Figure 7: Minimum Apparent MWIR Temperature Determination

It is interesting to compare the apparent temperature results, for a given operating temperature, to those attained in the previous effort by AMRDEC in developing the pathfinder projector. This pathfinder projector used a conductive cooling system, cooling only where the array and optical housing were in direct contact with the liquid cooled lines. In the pathfinder projector, no attempt was made to cool the projector walls. Also, the pathfinder projector employed an uncoated double-pane window with ~4% reflectance per surface. The FMS projector, in contrast, actively cools the interior walls and employs anti-reflective coatings on all optics and windows. Figure 8 below shows a plot of the apparent temperature attained with each projector. The FMS projector, even with significantly more optical elements, attains a lower apparent MWIR temperature for a given operating coolant temperature.

With independent cooling control over the emitter array and optics (via the heat-exchanger), it was also possible to individually characterize the contributions to the reduction in the observed background from each of these subsystems. A test was performed where only the emitter array was actively cooled. Apparent MWIR temperature measurements were conducted in the same manner as described above. Figure 8 below shows the apparent background temperature measured for array temperatures from -10 ºC to –33 ºC when only the array was cooled. This data is plotted under the "FMS IRSP w/warm optics" label. The lowest apparent MWIR background temperature attained while actively cooling only the emitter array was approximately 4 ºC. This required cooling the array to -33 ºC with a chiller set point of -40 ºC. Comparing to the performance shown under the "FMS IRSP" label, where the entire assembly was cooled, a significant improvement of 11 degrees was attained. Note, however, that this increased performance when cooling the entire assembly was also attained at a much higher operating temperature. When comparing the MWIR apparent temperatures for similar array temperatures (-15 ºC for example), the performance reduction is ~20 degrees lower for the fully cooled assembly. This is a significant improvement and justifies the additionally effort expended to cool the full assembly.

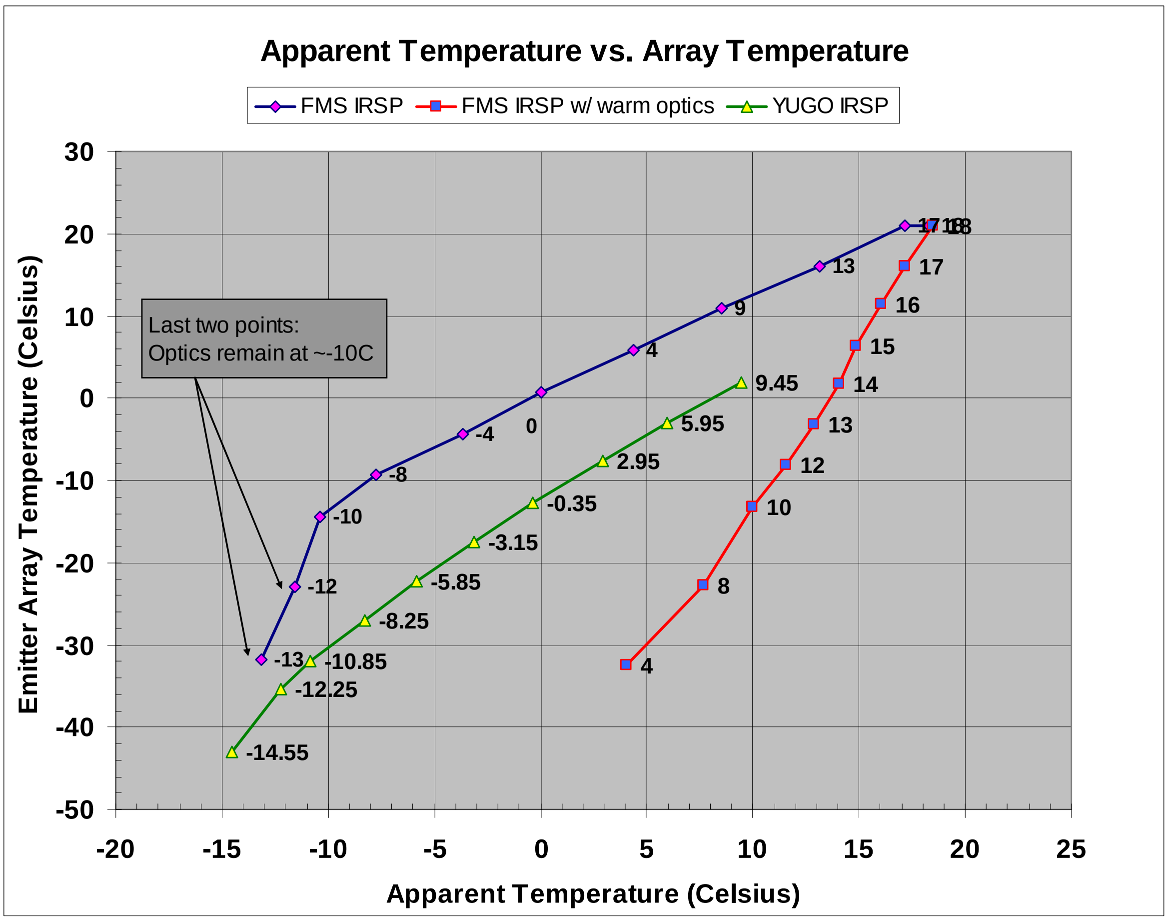

Figure 8: Min Apparent MWIR Temperature Comparison

The emitter array was operated with the internal assembly cooled and imagery was collected using an InSb MWIR camera. Two example images are shown in Figure 9 below.

Figure 9: FMS IRSP Example MWIR Imagery

4.5 Flight Table Mounting

The FMS IRSP was mounted to five-axis FMS for a preliminary check of mechanical clearance, weight balancing, and cable routing. Figure 10 shows a picture of the IRSP mounted to the fourth axis of the bow-tie FMS.

Figure 10: FMS IRSP on Flight Motion Simulator Table

5.0 LESSONS LEARNED AND FUTURE PLANS

The primary lesson learned with the previous year's efforts is the significant impact on the apparent background temperature observed when cooling the entire enclosure volume. For a given physical temperature of the emitter array, a significantly lower apparent background temperature can be attained by also cooling the enclosure volume (optics and walls).

The integration of numerous subsystems, conformity to volume constraints, and establishment of an enclosed, controlled environmental space required ingenuity and compromise. One requirement that could simply not be met without significant other sacrifices was the overall weight. The FMS IRSP was weighed in the configuration discussed within this paper. The total weight of the system mounted to the FMS was 105 lbs.

Work still remains in the path to full operational capability for the FMS IRSP. The primary component awaiting integration is the semiconductor laser point source, amplifier electronics, drive electronics, and subsequent mechanical interface. A room temperature mid-wave infrared quantum cascade laser has been selected for implementation, thereby removing the need to cryogenically cool the laser. A small on-board thermoelectric (TE) cooler will allow the laser to operate at temperatures below the optical system physical temperature. The TE cooler will provide a stable operational temperature to maintain stable power output and minimum wavelength shift.

6.0 CONCLUSIONS

The AMRDEC ASC has demonstrated performance of an FMS-mountable, cold background, two-dimensional, dynamic infrared projector system capable of achieving apparent background temperatures below 0ºC. This FMS IRSP provides the most advanced flight table compatible, cold background projector in operation.

ACKNOWLEDGEMENTS

We would like to thank all the government hardware-in-the-loop simulations personnel, especially Hajin Kim and Jim Buford. A special thanks to Bill Braselton, Kenny Crouch and John Ortakales with the Boeing Company and Steve Wilkerson and Mark Bowden with Optical Sciences Corporation.

REFERENCES

1. T. M. Cantey, D. B. Beasley, M. Bender; T. Messer, D. A. Saylor, J. A. Buford, "Cold background, flight motion simulator mounted, infrared scene projectors developed for use in AMRDEC Hardware-in-the-Loop facilities", SPIE Proceedings, Technologies for Synthetic Environments: Hardware-in-the-Loop Testing IX, SPIE Press, Orlando 2004

2. D. A. Saylor, D. B. Beasley, M. Bender; T. M. Cantey, J. A. Buford, "Characterization of Quantum Well Laser Diodes", SPIE Proceedings, Technologies for Synthetic Environments: Hardware-in-the-Loop Testing IX, SPIE Press, Orlando 2004.